

Estimations of changes of the Sun's mass and the gravitation constant from the modern observations of planets and spacecraft

E. V. Pitjeva^{1*}, N. P. Pitjev^{2**}

¹*Institute of Applied Astronomy of Russian Academy of Sciences, St.Petersburg*

²*St.Petersburg State University, St.Petersburg*

More than 635 000 positional observations of planets and spacecraft of different types, mostly radiotechnical ones (1961-2010), have been used for estimating possible changes of the gravitation constant, the solar mass, and semi-major axes of planets, as well as the value of the astronomical unit, related to them. The analysis of the observations has been performed on the basis of the EPM2010 ephemerides of IAA RAS in post-newtonian approximation. The EPM ephemerides are computed by numerical integration of the equations of motion of the nine major planets, the Sun, the Moon, asteroids and trans-neptunian objects.

The estimation of change for the geiocentric gravitation constant GM_{\odot} has been obtained

$$(\dot{GM}_{\odot})/GM_{\odot} = (-5.0 \pm 4.1) \cdot 10^{-14} \quad \text{in year} \quad (3\sigma).$$

The positive century changes of semi-major axes \dot{a}_i/a_i have been determined simultaneously for the planets Mercury, Venus, Mars, Jupiter, Saturn provided with high-accuracy sets of the observations, as expected if the geiocentric gravitation constant is decreasing in century wise. Perhaps, loss of the mass of the Sun M_{\odot} the produces change of GM_{\odot} due to the solar radiation and the solar wind compensated partially by the matter dropping on the Sun.

It was been found from the obtained GM_{\odot} change and taking into account the maximal limits of the possible M_{\odot} change that the gravitation constant \dot{G}/G falls within the interval

$$-4.2 \cdot 10^{-14} < \dot{G}/G < +7.5 \cdot 10^{-14} \quad \text{in year}$$

with the 95% probability.

The astronomical unit (au) is only connected with the geiocentric gravitation constant by its definition. The decrease of GM_{\odot} obtained in this paper should correspond to the century decrease of au. However, it has been shown that the present accuracy level of observations does not permit to evaluate the au change. The attained possibility of fining the GM_{\odot} change from high-accuracy observations points that fixing the connection between GM_{\odot} and au at the certain time moment is desirable, as it is inconvenient highly to have the changing value of the astronomical unit.

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*E-mail: `evp@ipa.nw.ru`

**E-mail: `ai@astro.spbu.ru`

INTRODUCTION

The whole array of high-precision observations of the planets and the development of modern planetary ephemeris form prerequisites for the study of very subtle effects, in particular, a change of the heliocentric gravitational constant GM_{\odot} with time. The question of variability and the possible rate of the change of gravitational constant G is regularly raised and considered in some cosmological theories (Uzan, 2003; 2009). The Sun's mass M_{\odot} , can not be absolutely constant too. On the one hand, it decreases due to continuous thermonuclear reactions and production of the radiant energy, with the matter carried away by the solar wind. On the other hand, there is a regular drop of interplanetary substances on the Sun, including dust, meteoroids, asteroids and comets.

In the history of the Sun there have possibly been the periods of positive and negative changes of the solar mass. In the initial period, shortly after the formation of the protosun and the beginning of nuclear reactions in it, the mass of the central body probably increased due to the continuing compression to the center of the initial cloud. During the formation of the planetary system, until the interplanetary space was cleared, the mass of the matter falling on the Sun was higher than the mass of the Sun reduced due to the light and corpuscular radiation. Now traces of the original, protosolar cloud are only likely to remain on the periphery of the Solar system beyond Neptune, the issue of the quantifying changes of the mass of the Sun still remains open because of the uncertainty of the overall balance including the mass loss due to radiation and the matter carried away by the solar wind, and the mass increase due to the matter falling on the Sun, in particular, comets whose collision with the photosphere of the Sun was repeatedly recorded by the SOHO space observatory (<http://ares.nrl.navy.mil/sungrazer/>). Any estimation is difficult because of the complexity of reliable estimation of falling matter mass as well as the time-varied intensity and the angular distribution of the solar wind in space. In this paper, we attempt to obtain experimental estimates of the change of the solar mass, namely, the heliocentric gravitational constant GM_{\odot} from the analysis of observational data of motion of planets and spacecraft.

The change of the value of the astronomical unit (au) is related to the change of the heliocentric gravitational constant. The astronomical unit is close in its magnitude to the average distance from the Earth to the Sun, but, by its definition it is only related to the heliocentric gravitational constant GM_{\odot} . From the obtained estimate \dot{GM}_{\odot} , we can estimate the possible change in time of the au value. This estimate can be compared with the direct change value of au obtained from observations.

EXPECTED EFFECTS OF THE CHANGE OF THE SUN'S MASS

Estimations of the mass change of the Sun and its rate repeatedly are cited in the papers related to the exploration of solar physics, the solar wind and radiation (e.g. Sunyaev, 1986; Livingston, 2000). The Sun's luminosity L_{\odot} somewhat varies during the eleven year cycle and the ~ 27 -day rotation around its axis; however, the fluctuations L_{\odot} do not exceed $0.1 \div 0.2\%$ (Frohlich, Lean, 1998; 2004). If we take the average total solar luminosity to be $L_{\odot} = 3.846 \cdot 10^{33}$ erg/s and the mass of the Sun $M_{\odot} = 1.9891 \cdot 10^{33}$ g (Brun et al, 1998), then the decrease of the mass of the Sun due to radiation as a fraction of the solar mass is equal to $\dot{M}_{\odot} = -6.789 \cdot 10^{-14} M_{\odot}$ per year.

The mass carried away with the solar wind was also repeatedly evaluated. The basic composition of the solar wind is as follows: approximately 95% — protons, 4% — nuclei of the helium atoms, and less than 1% — nuclei of atoms of other elements (C, N, O, Ne, Mg, Ca, Si, Fe) (Brandt, 1973; Hundhausen, 1976). The total number of particles flying away every second, is approximate by estimated as $1.3 \cdot 10^{36}$ (Kallenrode, 2004). The flow of the solar wind affects the activity of the Sun, coronal mass ejections. Typically, the average loss per year through the solar wind is estimated as $2 \cdot 10^{-14} M_{\odot}$ (Hundhausen, 1976; Hundhausen, 1997; Meyer-Vernet, 2007), that is, less than a third of the mass loss due to radiation. There are estimates $(2 \div 3) \cdot 10^{-14} M_{\odot}$ per year (Sunyaev, 1986; Carroll, Ostlie, 1996; Livingston, 2000), where a value of $3 \cdot 10^{-14} M_{\odot}$ can be considered the upper limit of the mass carried away by the solar wind. The cumulative effect of the relative annual decrease of the mass of the Sun due to radiation and the solar wind can be restricted by the inequality

$$-9.8 \cdot 10^{-14} < \dot{M}_{\odot}/M_{\odot} < -8.8 \cdot 10^{-14}. \quad (1)$$

The reverse process occurs due to the fall of the dust, meteor, asteroid and comet substance on the Sun. The dusty environment can not make a significant contribution to the

mass of the material fallen. According to the current data, the density of the interplanetary dust decreases with distance from the Sun, so that at the distance greater than 3 au there is not dust practically, with the 2/3ds of the interplanetary dust concentrating in particles of $10^{-5} \div 10^{-3}$ g, and the size of dust particles being mostly $1 \div 10 \mu m$ (Mann et al, 2010). The total mass of the dust matter is estimated approximately as $10^{19} \div 10^{20}$ g (Sunyaev, 1986). Even with the assumption that all the mass reaches the Sun in several thousands years, the rate of the dust fall-out particles will be less than $10^{-16} M_{\odot}$ per year. However, the dust particles smaller than 2 microns are swept by the solar pressure, while the ones greater than 2 microns move towards the Sun. The most part of the approaching dust sublimates within 0.1 au ($\sim 20 R_{\odot}$) and can not reach the surface of the Sun. It is also necessary to note, that a substantial part of the dust is carried away by the solar wind to the periphery of the Solar system (Mann et al., 2010). Therefore, the possible rate of the dust component falling out on the Sun is much smaller than $(10^{-16} \div 10^{-17}) \cdot M_{\odot}$ per year.

The larger particles, meteoroids and asteroids may fall on the Sun. Studies show that there is a constant migration of asteroids with an opportunity to complete the orbit evolution by the collision with the Sun (Farinella and et al, 1994; Gladman et al, 1997). The total number of small bodies is very large; the number of bodies larger than 1 km is about 1 million. A significant part of asteroids move within a region close to the orbit planes of major planets of the Solar system, mostly situated in the belt between the orbits of Mars and Jupiter. The current estimates of the total mass of the asteroid belt give $(13 \pm 2) \cdot 10^{-10} M_{\odot}$ (Pitjeva, 2010b), i.e. less than 10^{-3} mass of the Earth. For the ring to be able to exist for tens or hundreds millions of years, the fraction of the outgoing annually material should be significantly smaller than $10^{-7} \div 10^{-8}$ of the total mass of the asteroid belt, in case the main asteroid belt is not replenished from the outside. With the outgoing material falling on the Sun not regularly, we find that the upper limit of possible mass of the Sun drop-down material from the main belt is less than $(10^{-16} \div 10^{-17}) \cdot M_{\odot}$ per year. Thus, we obtain a significantly lower value (two to three orders of magnitude) than the decrease of the solar mass by radiation and solar wind, so in the solar neighbourhood and in the field of the main asteroid belt there is no sufficient interplanetary matter migrating to the Sun to be compared with the decrease of the solar mass due to radiation.

The mass of the matter that can come from distant regions of the solar system, mainly

in the form of comets (Bailey et al 1992), is more uncertain. There are trans-Neptunian areas — the Kuiper Belt, a cloud of the Hills, the Oort cloud. Currently, a large number of comets is detected in the immediate vicinity of the Sun (sungrazing comets) using the LASCO coronagraph (<http://lasco-www.nrl.navy.mil/>) installed at the SOHO solar space observatory (Marsden, 1989; 2005). Comets close to and often passing near the Sun are not long-living. They can disintegrate into fragments, or completely "fall apart". An example is a large family of Kreutz comets (Sekanina, Chodas, 2007). Some of them enter directly to the dense layers of the Sun. On the pictures of the SOHO observatory (<http://sungrazer.nrl.navy.mil/index.php>) the death of small fragments of comets in the solar photosphere is regularly recorded (kamikaze comet). The falling rocky bodies are more difficult to register, as during their approach to the Sun the glowing gas tail like that of icy objects and comets, does not form and the rocky bodies remain invisible. The overall contribution of the visible and invisible objects may be significant, although a reliable estimate of the total mass of substance reaching the Sun is extremely difficult. Nevertheless, the upper limits to the total mass can be specified. Statistics of comets discovered by the SOHO observatory gives about 500 comets for $30 \div 35$ months, on the average $170 \div 200$ comets per year. Many of them completely evaporate during their passage through the lower layers of the solar corona. There are registered repeatedly instances when the comets reached the photosphere. We assume that all the detected comets "vanished" and their mass increased the mass of the Sun, an overestimated value will result. The relatively small comets with the size from tens to hundreds meters are usually recorded, but for the upper estimate, we assume that the diameters of their nuclei (d_{com}) are several kilometers (as for the comets, which approach the spacecraft). If we take the average value of $d_{com} = 5$ km, the density of 3 g/cm^3 and double the result due to the missing and invisible falling objects, the annual upper bound is

$$\dot{M}_{\odot,com}/M_{\odot} < +3.2 \cdot 10^{-14}. \quad (2)$$

This estimate is comparable to values obtained for the mass loss of the Sun due to radiation and the solar wind, although it seems to be overestimated, as the large falling objects have not been actually registered. This value can be considered the upper limit of the possible increase of the solar mass due to the material falling in the form of comets, meteors, asteroids and dust.

Now one can point to the two sides of the common interval, probably overestimated, which should contain the value of $\dot{M}_{\odot}/M_{\odot}$. To obtain the lower limit, let us take the maximum loss estimate due to the solar wind, and at the same time, the zero drop of the material on the Sun. To find the upper limit, we use the maximum estimate (2) for the material falling on the Sun and the assumption that there is no mass loss due to the solar wind. Then, we obtain

$$-9.8 \cdot 10^{-14} < \dot{M}_{\odot}/M_{\odot} < -3.6 \cdot 10^{-14} \quad . \quad (3)$$

There are the restrictions to be kept in mind when trying to estimate the experimental changes of the Sun's mass.

THE INFLUENCE OF THE CHANGE OF THE SOLAR MASS ON ORBITAL ELEMENTS OF PLANETS

The change of the M_{\odot} solar mass must lead to the appearance of variations of elements of the planet orbits, but a small and monotonic change affects only some certain elements. The effect is sought from extremely the small expected change (of the order or less than $10^{-13}M_{\odot}$ per year), so it is sufficiently to consider the influence within the framework of the two-body problem (the Sun and the planet), as it is usually done, because the correction due to the influence of other bodies in the weak effect associated with the change of the central mass, is still several orders of magnitude smaller. The two-body problem with the variable mass has a long standing history and goes back to papers at the turn of the XIX and XX centuries by Gulden (1884), Meshchersky (1893), Stromgren (1903), Plummer (1906), etc. (see the detailed overview by Polyakhova, 1989). Variants of the isotropic mass variation in the two-body problem without the appearance of reactive forces, when no a particle is passed any pulse, were considered by MacMillan, Jeans, Armellini, Duboshin, Levi-Civita. A similar problem arises considering a possible change in time of the gravitational constant $G(t)$ under the Dirac's hypothesis (Dirac, 1938) leads to the change of the mutual attraction forces and accelerations between bodies, and the analogous equations of the two-body problem. The analysis of equations for the central field of a variable mass body within the framework of General Relativity is given in the paper by Krasinsky and Brumberg (Krasinsky, Brumberg, 2004).

If we denote $\mu(t)$ the product of $G(M_{\odot} + m)$, where m – the planet mass, the vector

equation of the relative motion for a body with mass m is written

$$\ddot{\mathbf{r}} = -\frac{\mu(t)}{r^3}\mathbf{r}. \quad (4)$$

In general, we can assume that the gravitational constant G , incoming in $\mu(t)$, may depend on time. Since the central field remains while $\mu(t)$ (4) changes, then the area integral remains too, which is obtained immediately if the left and right side of (4) to vector multiply on \mathbf{r} :

$$\mathbf{r} \times \ddot{\mathbf{r}} = 0 \quad \text{or} \quad \frac{d}{dt}(\mathbf{r} \times \dot{\mathbf{r}}) = \mathbf{0},$$

then

$$\mathbf{r} \times \dot{\mathbf{r}} = \mathbf{c}. \quad (5)$$

The flat motion follows from the existence of the vector area integral (5). Energy for the case of the time-dependent value of $\mu(t)$ is changing and is not more the integral of motion. Taking into account the monotony and smallness of the change of $\mu(t)$, it was shown (Jeans, 1924), that the invariant holds

$$\mu(t) * a(t) = \text{const}, \quad (6)$$

where a – is the orbital semi-major planet axis. Sometimes this relation is called the adiabatic invariant of Poincare-Jeans, so as the first conclusion (6) was made by Poincare (Poincaré, 1911). The assumption, that $\mu(t)$ varies rather slowly, is essential for derivation of this result (Gelfgat, 1965). In our case, the expected value for Sun $|\dot{\mu}_{\odot}(t)/\mu_{\odot}(t)| \sim 10^{-13}$ per year is much orders of magnitude smaller than it is required by the Gelfgat's constraints.

Since the plane of motion is preserved, then the elements (i, Ω) , determining the position of the orbital plane, do not change. It should be considered the dependence of semi-axis $a = a(t)$, the eccentricity $e = e(t)$ and the argument of pericentre $g = g(t)$ of the osculating elliptical orbits from the characteristics of the $\mu(t)$ change for instantaneous values of coordinates, velocities, and a mass. From (6) we find a relationship between the changes of $\mu(t)$ and $a(t)$:

$$\frac{\dot{\mu}}{\mu} = -\frac{\dot{a}}{a}. \quad (7)$$

The relationship obtained from the integral of areas for the osculating orbit is

$$\mu(t) * a(t) * (1 - e^2) = c^2, \quad \text{where} \quad c = |\mathbf{c}|, \quad (8)$$

therefore, using (6), the e eccentricity of the osculate orbit remains constant under the given conditions $e = \text{const}$ (Jeans, 1925). Investigation of the change of the g pericentre position

for the small and monotonic $\mu(t)$ change was made in the paper (Kevorkian, Cole, 1996), where it was shown that under accepted conditions of the smallness and monotony of $\dot{\mu}$, the g value does not have a secular trend, and there may be only small oscillations with the small amplitude of order $(\dot{\mu}/\mu)^2$.

The change in time of $a = a(t)$, as $\mu(t)$, leads to the change of the period of the body m that is leaving from the position for the case $\mu = \text{const}$, and the increase of deviation will depend quadratically on the time interval.

The possible $\mu_{\odot}(t) = GM_{\odot}$ change in the Solar system should be appeared in a systematic, progressive, although very small deviation of the body position on the orbit (that is their longitude) and the change of the a_i semi-major axes proportionally to the $\mu_{\odot}(t)$ change with opposite sign (7). The fact that the value $\mu(t) = G(M_{\odot} + m)$ includes the m mass of a planet does not change the situation, since taking into account the mass m of a planet leads to the correction by several orders less.

Thus, when the area integral remains and the attractive force from the main body decrease/increase monotone, the second body is moving along the trajectory gradually receding/approaching from/to the central body. The relative increase of the distance is equal to the relative decreasing of mass of the central body and vice versa. An orbit is transforming gradually remaining identical to itself, and is of a spiral form. The $GM_{\odot}(t)$ change does not lead to secular trends of the eccentricity and the longitude of perihelion. The semi-axis is century changing $a = a(t)$. Thus it is necessary to look for the effect caused by possible change in time of the heliocentric gravitational constant in the corresponding secular variation of the semi-axes of the planet orbits.

OBSERVATIONAL MATERIAL, REDUCTION OF OBSERVATIONS

More than 635,000 positional observations of planets and spacecraft of various types (Table 1), mainly radiotechnical (1961-2010) have been used to construct high-precision ephemerides of planets and to determine the change of the heliocentric gravitational constant. The very accurate observations are required to find the very small effects, and it is most important and desirable to have observational data for planets, close to the Sun and having shorter periods, in the first place, the data for Mercury and Venus. Radiotechnical measurements which began in 1961 and are continuing with rising numbers since, first, yielded two new types of measurements in astrometry: the distance and the relative speed,

and secondly, the accuracy of the measurements became several orders of magnitude greater than the accuracy of the optical observations.

Table 1. The observations used

Observation type	Time interval	Observation number
Optical	1913–2009	57768
Radiotechnical	1961–2010	577763
Total		635531

For this reason, the ephemerides of the inner planets provided by radiotechnical observations (mostly, data of time delays) are based fully on these data. At present, the radiolocation of planet surfaces is not carried out, but trajectory data of various spacecraft that orbiting around planets or passing near them are received regularly. Accuracy of observations of ranging has improved from 6 km to several meters for today’s data of the spacecraft. It is necessary to say that the ephemerides of the outer planets so far, mainly, are based on optical measurements since 1913, when at the Naval Observatory of USA the improved micrometer was introduced, and observations become more accurate ($0''.5$).

Table 2. The distribution of optical observation and rms residuals in mas, 1913–2009

Planet	Observation number	σ
Jupiter	13038	190
Saturn	16246	150
Uranus	11672	188
Neptune	11342	177
Pluto	5470	141
Total	57768	

However, until now a complete rotation period of Neptune and Pluto is not provided by the observations. In addition to optical observations of these planets, for the construction of ephemerides and estimation of their parameters the absolute observation satellites of the outer planets are used, as these observation are more precisely, and practically free from the phase effect hard taking into account, which is in observations of the planets themselves.

Modern optical data are the CCD observations, their accuracy reaches $0''.05$. The number of used optical and radio observations, their planet distribution, as well as mean square error of residuals of observations are given in Table. 1 - 3.

Table 3. Distribution, time interval, number and rms residuals for radiometric observations

Planet	Data type	Time interval	Observation number	σ
Mercury	τ [m]	1964–1997	937	575
	τ [m]	1973–2009	5	31.0
	α, δ [mas]	2008–2009	6	2.1
Venus	τ [m]	1961–1995	2324	584
	Magellan dr [mm/s]	1992–1994	195	0.007
	MGN,VEX VLBI α, δ [mas]	1990–2007	22	3.0
	VEX τ [m]	2006–2009	28163	3.6
	Cassini τ [m]	1998–1999	2	2.4
	Cassini α, δ [mas]	1998–1999	4	105
Mars	τ [m]	1965–1995	54851	738
	Viking τ [m]	1976–1982	1258	8.8
	Viking $d\tau$ [mm/s]	1976–1978	14978	0.89
	Pathfinder τ [m]	1997	90	2.8
	Pathfinder $d\tau$ [mm/s]	1997	7569	0.09
	MGS τ [m]	1998–2006	165562	1.4
	Odyssey τ [m]	2002–2008	293707	1.2
	MRO τ [m]	2006–2008	7775	1.6
	spacecraft VLBI α, δ [mas]	1984–2010	136	0.6
Jupiter	τ [m]	1973–2000	7	13.8
	spacecraft α, δ [mas]	1973–2000	16	5.0
	spacecraft VLBI α, δ [mas]	1996–1997	24	9.5
Saturn	τ [m]	1979–2006	34	3.5
	α, δ [mas]	1979–2006	92	0.4
Uranus	Voyager-2 τ [m]	1986	1	7.4
	Voyager-2 α, δ [mas]	1986	2	11.0
Neptune	Voyager-2 τ [m]	1989	1	22.9
	Voyager-2 α, δ [mas]	1989	2	3.7
Total			577763	

The most accurate and long series of observations are available for Mars for which space-

craft and landers were launched repeatedly. Radiotechnical observations relating to Venus are much smaller, there are spacecraft Magellan and Venus Express. A situation for observations of Mercury is much worse. The Messenger spacecraft (NASA) on the orbit around it have just appeared and we have not these data. There were only one-time conjunctions of Mariner-10 (1974–1975) and Messenger (2008–2009) spacecraft and ranging for the Mercury surface (1964–1997). Situation should be changed after the new data from the Messenger spacecraft and from the future spacecraft BepiColombo (ESA, launch 2014) will be available. There are a number of radiotechnical observations for Jupiter and Saturn: the data for several spacecraft for Jupiter, and data of the Cassini spacecraft for Saturn. For Uranus and Neptune there are one 3-D points (α, δ, R) , resulting from the conjunction of Voyager-2 with these planets. The data were taken from the JPL database (<http://ssd.jpl.nasa.gov/iau-comm4/>), created by Dr. Standish, and now supported by Dr. Folkner and the VEX data sent due to kindness of Dr. Fienga, as well as supplemented by rows of American and Russian radar observation of planets 1961–1995, taken from various sources. Russian radar observations of planets, along with their references are stored on the site of IAA RAS <http://www.ipa.nw.ru/PAGE/DEPFUND/LEA/ENG/englea.htm>. The brief description of astrometric radio observations can be found in Table. 2 by Pitjeva (2005).

EPM2010 PLANETARY EPHEMERIDES, DETERMINED PARAMETERS

This work is based on the EPM2010 planetary ephemerides of IAA RAS. Numerical ephemerides of motion of the planets and the Moon (EPM — Ephemerides of Planets and the Moon) began to create in the seventieth years of last century under the leadership of G.A. Krasinsky for support of Russian space flights, and has successfully developed since then. The version of the EPM2004 ephemerides has used to release the Russian “Astronomical Yearbook” described in (Pitjeva, 2005), the version of the EPM2008 ephemerides in the paper (Pitjeva, 2010a). The EPM2010 ephemerides were constructed using more than 635 thousands of observations (1913-2010) of different types. EPM2010 differ from the previous versions by the improved dynamic model of motion of Solar system bodies, adding the perturbation from the ring of Trans-Neptunian objects (TNO), the new value of the Mercury mass, defined due to the three encounters of the Messenger spacecraft with Mercury, improvement of reductions of observations with the addition of the relativistic delay effect from Jupiter and Saturn, and the expanded database of observations, including radiotechnical (2008 -

2010) and CCD (2009) measurements.

Ephemerides were constructed by the simultaneous numerical integration of equations of motion of all the major planets, the Sun, the Moon, the largest 301 asteroids, 21 TNO, the lunar libration, taking into account the perturbations from the oblateness of the Sun and the asteroid belt, lying in the ecliptic plane and consisting of the remaining smaller asteroids, as well as the ring of the TNO rest at the mean distance of 43 au. The equations of motion of the bodies were taken in the post-Newtonian approximation in the Schwarzschild field. Integration in the barycentric system of coordinates for the epoch J2000.0 performed by the Everhard method over 400 years (1800-2200) by the lunar and planetary integrator of the software package ERA-7 (Krasinsky, Vasilyev, 1997). The accuracy of numerical integration was verified by comparing the results of the forward and backward integrations over the century of the time interval. The errors were at least order of the magnitude smaller than the accuracy of observations. Thus, the accuracy of the ephemeris is determined mainly the accuracy of observations and their reductions.

In the basic version of the improved EPM2010 planetary ephemeris about 260 parameters are determined: elements of the orbits of the planets and the 18 satellites of the outer planets; value of the astronomical unit; three angles of the orientation with respect to the ICRF frame; 13 parameters of the rotation of Mars and the coordinates for the three martian landers; masses of 10 asteroids, the mean density for the three taxonomic classes of asteroids (C, S, M), the mass and radius of the asteroid belt, the mass of the TNO ring, the ratio of the mass of the Earth and the Moon; quadrupole moment of the Sun (J_2) and 23 parameters for the solar corona of different conjunctions of the planets with the Sun; eight coefficients of the topography of Mercury and the corrections to the level surface of Venus and Mars, constant shifts for the three series of planetary radar observations and for 7 spacecraft; 5 coefficients for the additional effect of the phase of the outer planets.

The accuracy of EPM ephemerides was tested by comparison with the observations (all residuals do not superior to their a priori errors), as well as comparison with the DE421 (JPL) independent ephemerides, those are in a good agreement (Pitjeva, 2010a).

After constructing the EPM2010 ephemerides to all the observations the some other parameters can be to estimate: the changes of the GM_\odot heliocentric gravitational constant, the G gravitational constant, semi-axes of the planet orbits, and the astronomical unit.

OBTAINED ESTIMATES OF THE M_\odot, G, a_i CHANGES

The main problem of this case consists in the smallness of the effects that need to be revealed. It was impossible to do this before an appearance in recent years a quite large number of high-precision observations, including data from spacecraft. Accuracy of determination of the parameters increased significantly also due to extension of the time interval for which there are high-precision sets of planet observations.

The parameters \dot{G} and \dot{GM}_\odot were fitted by the least squares method simultaneously with all basic parameters of ephemerides, but each separately, i.e. they are considered in different solution versions. If \dot{GM}_\odot is found then it is taken into account that the accelerations between the Sun and other bodies change, and the mutual attractions between other pairs of bodies remain. This differs from the situation when we find the change of G and when the forces between all bodies vary accordingly. It should be noted that for the version of the \dot{G} definition from the planet motions, the main contribution makes by the Sun, since the equations of the planet motions include products of the masses on the gravitational constant, among them the term for the Sun (GM_\odot) is the main one of several orders of magnitude more than the others. Therefore, separating the change of G from the change M_\odot with the dominant term of the GM_\odot is impossible. In this regard, it is more correctly (and reliably) to determine from planet motions the change of GM_\odot instead of \dot{G} or \dot{M}_\odot separately.

Table 4. The secular change values of the semi-major axes for the 6 planets provided with the high-accuracy observations

Planet	\dot{a}/a (century $^{-1}$)	Correlation coefficients between \dot{a} and a
Mercury	$(3.30 \pm 5.95) \cdot 10^{-12}$	56.5%
Venus	$(3.74 \pm 2.90) \cdot 10^{-12}$	95.8%
Earth	$(1.35 \pm 0.32) \cdot 10^{-14}$	0.6%
Mars	$(2.35 \pm 0.54) \cdot 10^{-14}$	0.4%
Jupiter	$(3.63 \pm 2.24) \cdot 10^{-9}$	20.2%
Saturn	$(9.44 \pm 1.38) \cdot 10^{-10}$	35.9%

Table. 4 shows the values obtained for the relative change of semi-major axes of the planet orbits. The most accurate results connect with availability of observations obtained

with using radiotechnical equipment, in particular using the spacecraft observations and the duration of larger time intervals. Accordingly, the most reliable relative values of \dot{a}/a have been received for them. These are the results for all the inner planets from Mercury to Mars. For Jupiter and Saturn the accuracy of \dot{a}/a is less. Values for the planets, not provided by radiotechnical data are unreliable. It is important that all the values obtained for the planets from Mercury to Saturn show the positive values of the \dot{a}/a ratio, i.e., indicate the decrease in time of the GM_{\odot} heliocentric gravitational constant (7).

The change of the GM_{\odot} heliocentric gravitational constant has been determined from fitting all observations:

$$(G\dot{M}_{\odot})/GM_{\odot} = (-5.04 \pm 4.14) \cdot 10^{-14} \text{ per year } (3\sigma). \quad (9)$$

This was made similarly to find \dot{G}/G :

$$\dot{G}/G = (-4.96 \pm 4.14) \cdot 10^{-14} \text{ per year } (3\sigma). \quad (10)$$

The closeness of the results (9) and (10) is not surprising, since while finding the \dot{G}/G , when the forces between all pairs of bodies change, the effect of the central body is dominant and again the effect of GM_{\odot} is found practically, instead of G . From the result (9) obtained for GM_{\odot} , it is possible to estimate the \dot{G} value using the relation

$$\dot{\mu}_{\odot}/\mu_{\odot} = \dot{G}/G + \dot{M}_{\odot}/M_{\odot}. \quad (11)$$

This relation is valid with the 95% (2σ) probability:

$$-7.8 \cdot 10^{-14} < \dot{G}/G + \dot{M}_{\odot}/M_{\odot} < -2.3 \cdot 10^{-14} \text{ year}^{-1}. \quad (12)$$

Hence, using the limits (3) found for the value $\dot{M}_{\odot}/M_{\odot}$, we obtain the \dot{G}/G value with the 95% probability is within the interval

$$-4.2 \cdot 10^{-14} < \dot{G}/G < +7.5 \cdot 10^{-14} \text{ per year}. \quad (13)$$

Note, the \dot{G}/G estimate, obtained in 2004 from the lunar laser ranging (Williams et al, 2004), which in any case is not complicated by the possible change of the solar mass, gives the following values of the limits for the gravitational constant change: $\dot{G}/G = (4 \pm 13) \cdot 10^{-13}$ per year. The estimate of $(G\dot{M}_{\odot})/GM_{\odot}$ obtained by us (9) has the opposite sign and its value is an order of magnitude smaller.

The obtained change of GM_\odot , most probably, is related to the change of the Sun's mass M_\odot , rather than to the G change. Thus, we have

$$\dot{M}_\odot/M_\odot = (-5.0 \pm 4.1) \cdot 10^{-14} \quad \text{per year} \quad (3\sigma). \quad (14)$$

Note that this value hits the limitation interval (3) for \dot{M}_\odot/M_\odot . The obtained change of GM_\odot (9), possibly, reflects the balance between the mass loss due the radiation and the solar wind and the falling material contained in comets, rocky debris and asteroids, which do not produce the visible glowing gas tail.

THE POSSIBLE CHANGE OF THE ASTRONOMICAL UNIT

The change of the astronomical unit is connected with the change of the heliocentric gravitational constant. The astronomical unit, although is close in magnitude to the average distance of the Earth from the Sun, but by its definition (resolution MAS 1976 - IAU, 1976) is connected with the heliocentric gravitational constant:

$$GM_\odot[m^3s^{-2}] = k^2 \cdot \text{au}^3[m^3]/86400^2[s^2], \quad (15)$$

where $k = 0.01720209895$ is Gaussian gravitational constant. Currently, au is determined from ranging data with very high real accuracy, allowing to deduce the value of the heliocentric gravitational constant from the of value $\text{au} = (149597870700 \pm 3) \text{ m}$, using the relation (15): $GM_\odot = (1327124404 \pm 1)[km^3s^{-2}]$ (e.g., Pitjeva and Standish, 2009), which coincides with the value GM_\odot , proposed by W.Folkner and obtained by the same method. These values of au and GM_\odot for the TDB time scale were approved at the XXVII IAU General Assembly (2009) as the best current values of astronomical constants (http://maia.usno.navy.mil/NSFA2/NSFA_cbe.html).

In the paper by Krasinsky and Brumberg (Krasinsky, Brumberg, 2004) from ranging data 1961 – 2003, using a numerical theory of planetary motion, about coinciding with the EPM2004 (Pitjeva, 2005), the authors obtained the secular increase of the astronomical unit $\dot{\text{au}} = 15 \text{ m per century}$, which should correspond to the increase of the heliocentric gravitational constant

$$G\dot{M}_\odot/GM_\odot \simeq 3 \cdot 10^{-12} \quad \text{per year}. \quad (16)$$

The positive change of au should correspond to the decrease of semi-major axes of planet orbits, and not vice versa, as sometimes this is claimed, and alternative theories of gravity

(Miura T. et al, 2009; Nyambuya G.G., 2010) are even constructed on this incorrect basis. Such the large positive change (16) of the does not correspond to estimations of physical processes in the Solar system (the solar radiation and wind, the matter falling on the Sun), and also to the estimate (9) obtained in this study: $\dot{GM}_{\odot}/GM_{\odot} = -5.04 \cdot 10^{-14}$ per year. However, authors considered themselves that the increase of au and the heliocentric gravitational constant (16) are rather parameters of agreement than the real change of the physical parameters.

Analysis of the obtained results based on the observations described in this paper, and the EPM2010 ephemerides, shows that the present level of observational accuracy does not permit to evaluate the au change. In the paper by Krasinsky and Brumberg the au change was determined simultaneously with all other parameters, specifically, with the orbital elements of planets and the value of the au astronomical unit itself. However, at present it is impossible to determine simultaneously two parameters: the value of the astronomical unit, and its change. In this case, the correlation between au and its change \dot{au} reaches 98.1 %, and leads to incorrect values of both of these parameters, in particular, gives \dot{au} the order of 15 m per century.

Without the simultaneous determination of au and \dot{au} , i.e. if only the change of the astronomical unit is estimated, together with other parameters, the \dot{au} value is about 1 m per century, and does not exceed its formal uncertainty, thus it is determined:

$$\dot{au} = (1.2 \pm 3.2) \text{ m/cy } (3 \sigma).$$

Furthermore, including or excluding the \dot{au} value from the number of the solution parameters does not change the observation residuals, the mean error of the unit weight is also not changed ($\Delta\sigma \simeq 0.2\%$), so there is no reason to assume that \dot{au} is the necessary parameter of agreement, and include it in the number parameters to be estimated.

The modern accuracy has approached to the level when it is possible to estimate the change of the heliocentric gravitational constant GM_{\odot} , therefore it is desirable to specify the definition of the astronomical unit, for example, by fixing the connection between GM_{\odot} and au at the certain time moment, as it is inconvenient highly to have the changing value of the astronomical unit.

CONCLUSION

Modern radiotechnical observations of the planets and spacecraft having the meter ac-

curacy (relative error of $10^{-12} \div 10^{-11}$) make it possible to obtain estimates of very small effects in the Solar system. The significant progress is related to several factors: increase in accuracy of reduction procedures for observations and in dynamical models of planet motion, as well as improvement of the quality of observational data, increasing their accuracy and the time interval in which these observations are obtained.

The results obtained indicate on the decrease of the heliocentric gravitation constant per year at the level

$$G\dot{M}_{\odot}/GM_{\odot} = (-5.0 \pm 4.1) \cdot 10^{-14} \quad (3\sigma).$$

For the gravitation constant it is found that value of \dot{G}/G falls in the interval

$$-4.2 \cdot 10^{-14} < \dot{G}/G < +7.5 \cdot 10^{-14}$$

with the 95% probability.

The obtained change of GM_{\odot} seems to be due to the change of the solar mass M_{\odot} , rather than the G change and reflects the balance between the loss of the solar mass due to by the radiation and the solar wind and matter falling on the Sun. It is possible to make the cautious conclusion that at present in the Solar system there is still the significant effect of matter falling on the Sun, that compensate partly the effect of reducing the solar mass due to the radiation and the solar wind.

In the future, the connection between GM_{\odot} and au (15) should be fixed at the certain time moment, as it is inconvenient highly to have the changing value of the astronomical unit; moreover, it should be to define the changes GM_{\odot} , M_{\odot} , G rather than the change of the astronomical unit.

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